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Extension of reflection-mode digital gradient sensing method for visualizing and quantifying transient deformations and damage in solids

Amith S. Jain, Hareesh V. Tippur *

Department of Mechanical Engineering, Auburn University, AL 36849, USA

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ABSTRACT

The reflection-mode Digital Gradient Sensing (r-DGS) method is extended to visualize and quantify dynamic deformations in solids due to stress wave propagation and for damage/disbond detection in layered materials due to impact loading. The r-DGS technique employs digital image correlation principles to quantify two orthogonal surface slopes simultaneously in specularly reflective solids. Here, for the first time, r-DGS has been implemented in conjunction with ultrahigh-speed photography to quantitatively map surface slopes during stress wave propagation in a thin plate due to an impact event. The measured surface slopes have also been used to successfully evaluate instantaneous topographic information. The r-DGS method has been subsequently demonstrated to be an effective tool for detecting disbonds in layered structures subjected to impact loading. Baseline experiments in each category have been carried out to demonstrate the methodology.

1. Introduction

Thin structures experience rapid loading in a variety of engineering scenarios. Examples include tool drop and pebble impact on airframe panels, hail damage of windows and automotive windshields, etc. Visualization and quantification of deformations and damage in these and other similar situations is important for failure characterization and non-destructive evaluation (NDE) of solids and structures. In thin structures, elastic stresses are proportional to curvatures and hence quantifying them accurately would help assess their mechanical response and integrity when used in conjunction with failure theories. Measuring surface slopes directly using non-contact, full-field methods is valuable for such applications. That is, slope measurements offer unique advantages over measuring out-of-plane displacements because a single step integration or differentiation of measured data could yield topography or curvatures, respectively, of thin structures. In doing so, numerical errors due to two successive differentiations of displacements can be avoided if curvatures are to be determined using measured out-of-plane displacements.

Several techniques have been proposed for measuring surface slopes and curvatures of solids over the years. They can be broadly classified into incoherent and coherent methods based on white light or laser light illumination. Among the former type, the slope measurements based on Lichtenberg's reflection moiré concept [1] has taken hold in numerous forms. Kao and Chiang [2] have described several such moiré methods for visualizing and quantifying surface slopes and curvatures. Ritter [3] has demonstrated the method for studying dynamic problems including vibrating plates. Optical differentiation by superposing spatially shifted moiré fringes representing displacements and slopes were also discussed. Among the grating-based real-time interferometers, the early work of Assa et al. [4] is notable. They have proposed a shearing interferometer for measuring slopes and curvatures which can account for the initial curvature of the model. The works of Tippur and his co-workers has resulted in a grating-based lateral shearing interferometry called the Coherent Gradient Sensing (CGS) [5] method to quantify real-time surface slopes and curvatures [6–8] of thin films and structures. Many other double exposure and single exposure techniques [9–14] are also reported in the literature for measuring slopes and curvatures of specularly and diffusely reflective surfaces.

Recently, digital image correlation methods have become rather popular for measuring 2D and 3D deformations [15–19] in a

* Corresponding author.: Tel: +1 334 8443327.
E-mail address: tippuhv@auburn.edu (H.V. Tippur).

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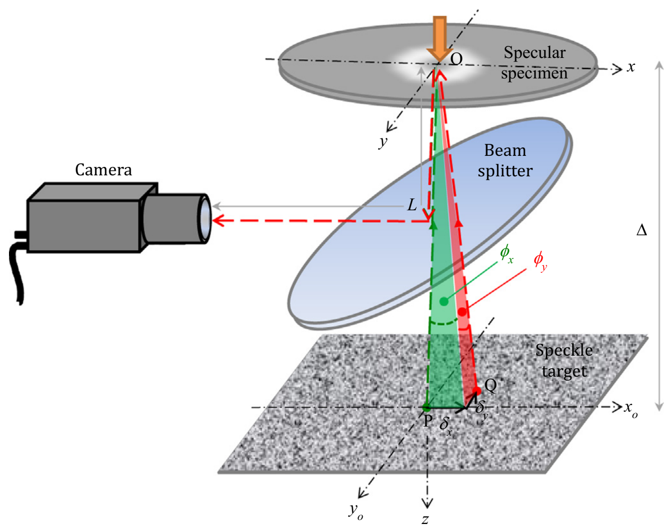

Fig. 1. Schematic depicting the experimental setup and working principle of reflection-mode DGS (r-DGS) methodology.

variety of static and dynamic experimental mechanics problems. In this context, Periasamy and Tippur have recently proposed a new method called Digital Gradient Sensing (DGS) [20,21] based on digital image correlation principles for measuring angular deflections of light rays in planar phase objects. They have related angular deflections of light rays to planar stress gradients. Subsequently, they have modified DGS to study reflective objects by mapping orthogonal surface slopes simultaneously and curvatures [22]. The simplicity of its optical arrangement, ubiquitous commercial and freeware image correlation software packages, and technological advances in terms of high pixel and gray scale resolutions of sensors can all be readily leveraged to further advance this new approach for experimental mechanics and NDE. Further, the method can be in principle extended using other wavelengths of light such as infrared to circumvent the limitation of object surface specularity in visible wave lengths. In view of these, the current work deals with extending DGS to slope measurement in thin structures during stress-wave dominant situations and for impact induced damage detection.

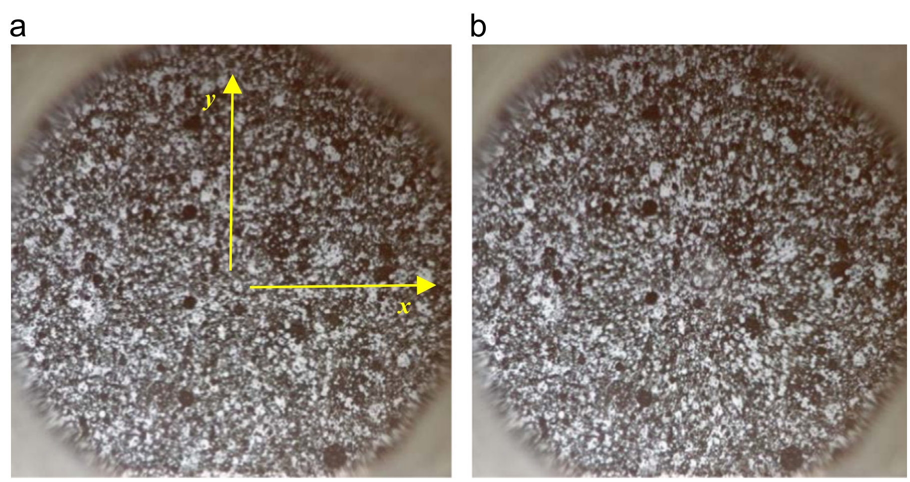

Fig. 2. Recorded speckles from the target plane for r-DGS demonstration. (a) Reference image, (b) Deformed image with 30 μm central deflection. (Δ = 65 mm, Si wafer diameter 50.8 mm).

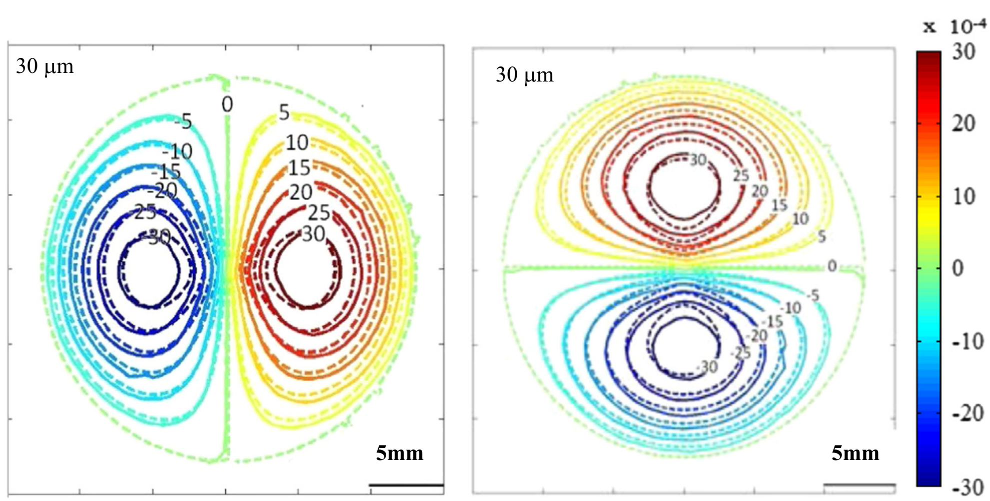

Fig. 3. Experimental (solid lines) and analytical (broken lines) contours of surface slopes $\frac{\partial w}{\partial x}$ (left) and $\frac{\partial w}{\partial y}$ (right) for a clamped silicon wafer subjected to 30 μm central displacement in the z-direction. Contour levels are in 5 x 10^{-4} radian increments; L = 1217 mm and Δ = 65 mm.